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SUPPORTING INFORMATION

Explaining patterns of avian diversity and endemism:

Climate and biomes of southern Africa over the last 140,000 years

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Appendix S2 Supplementary Text

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Simulated changes in biome extent and location

Desert Biome

The Desert biome was simulated to have a mean extent only about two-thirds of its present extent, with generally reduced extents for most last glacial stage climates. It was at its smallest extents under Heinrich Event climates (Figs. 3 & 4), reaching a minimum extent (8.8% of 1961–90, Table S4 in Appendix S3) under the H2 climate and dominating no grid cells under the H0 climate (Table S5 in Appendix S3). Especially during the Holocene and prior to ca. 80 ka this biome was simulated to reach greatest extents during summer insolation minima, i.e. when the monsoon intensity is simulated to have been minimal (Fig. 4), with its maximum extent overall being simulated for 124 ka, when it dominated more than twice as many grid cells as it does today. At such times it extended principally southwards and eastwards. Although the biome was simulated to occur consistently in four grid cells on the Namibian coast (Fig. S3(a) in Appendix S3), no grid cells were consistently dominated by this biome (Fig. 5(a)), the most frequently dominated being two grid cells on the central Namibian coast just north of the Tropic of Capricorn that were simulated as dominated by the biome for more than 60 of the time slices. A majority of the grid cells that were simulated to be dominated by this biome for at least one time slice were so dominated under ten or fewer of the climate scenarios considered (91 of 140, Table S6 in Appendix S3).

Succulent Karoo Biome

The Succulent Karoo biome was simulated to have been more extensive than today for most palaeoclimate time slices (Figs. 3 & 4), with a mean extent 25% greater than today (Table S4 in Appendix S3). As with the Desert biome, however, it was simulated to have much reduced extents under the Heinrich Event climates, reaching minimum extent under the H5 climate. It also paralleled the Desert biome in having greatest simulated extents broadly coinciding with summer insolation minima, its maximum extent, of more than double its present extent, being simulated for 34 ka. At such times it was simulated to extend eastwards into Eastern Cape, and also often to the north-east and/or east of the area simulated to be occupied by the Nama Karoo. It also was often simulated to have a greater extent in Namibia and extending northwards as far as south-western Angola (Fig. 3). This biome was simulated to occur across all 79 time slices in forty grid cells (Fig. S3(b) in Appendix S3), and eleven grid cells were simulated to be consistently dominated by the biome (Fig. 5(b)). The latter grid cells form a contiguous block, principally in coastal southern Namibia but extending into Northern Cape, and are surrounded by 36 cells that are

simulated to be dominated by the biome for at least 71 of the climate scenarios considered (Table S6 in Appendix S3).

Nama Karoo Biome

The Nama Karoo biome was simulated to have been more extensive than at present for most palaeoclimate time slices (Figs. 3 & 4), with a mean extent ca. 150% of that for 1961–90 (Table S4 in Appendix S3). For the majority of time slices, including those close both to the last glacial maximum (LGM, e.g. 22 ka) and to the last interglacial (LIG) ‘optimum’ (124 ka), it was simulated to have extended both eastwards and northwards beyond its present extent. Especially before ca. 45 ka, it showed fluctuations in extent that followed the variation in summer insolation, with maximum extents shortly after insolation minima (Fig. 4). At 116 ka (Fig. 3), which corresponds to the later part of the LIG in terrestrial records (Brauer *et al.*, 2007), shortly follows the transition to Marine Oxygen Isotope (MOI) Sub-stage 5d in marine records (Martinson *et al.*, 1987), and corresponds to an insolation maximum, this biome is approaching a minimum in extent and is similar in extent and location to the present day (Fig. 3 and Table S4 in Appendix S3) when insolation is once again approaching a peak. The climatic conditions simulated for Heinrich Events, however, led to simulated very much reduced extents, the most extreme simulated reduction being for the H0 climate when this biome was simulated to have been little more than a quarter of its present extent, although the reduction in extent was almost as great for H2 and H4 and the number of grid cells dominated by this biome was at a minimum during H2 (Table S5 in Appendix S3). Although this biome was simulated to have occurred consistently in 52 grid cells (Fig. S3(c) in Appendix S3), no grid cells were simulated to have been consistently dominated by the biome (Fig. 5(c)). Although a relatively large block of cells (47) that corresponds to the core of the biome today was simulated to have been dominated by the biome for 71 or more of the climate scenarios considered, these cells were not simulated to have been dominated by the biome under at least some Heinrich Event climates, when Savanna or Grassland were instead simulated as the dominant biome.

Fynbos Biome

The Fynbos biome was also simulated to have been generally more extensive than at present (Figs. 3 & 4, Table S4 in Appendix S3), although in this case most of that additional extent resulted from simulated areas of this biome in the north of the region in areas that are remote and disjunct from the present core area of the biome that is centred in Western Cape. Although simulation of extensive Fynbos in these latter areas

must thus be treated with some caution, there is palynological evidence indicating the presence of characteristic Fynbos taxa, including Restionaceae and Ericaceae, in these northern areas during the last glacial (Shi *et al.*, 1998, 2000), and the regional geology is compatible with the development of renosterveld, a Fynbos variant associated with heavier soils derived from shale bedrocks. In marked contrast to the three preceding biomes, peak extents of this biome were simulated for the Heinrich Event climates, with a simulated extent about three times that of the present for the H3 climate. At these times the core area of the biome was simulated generally to extend further northwards than today up the west coast, as far as southern Namibia. The biome was also simulated to be particularly extensive in the north of the region at these times, especially in northern parts of Namibia and Botswana. The extent of the biome was also simulated to show fluctuations related to insolation variations, although with peak extents tending to follow insolation peaks, the fluctuations thus being more or less directly anti-phase to those shown by the extents of the Nama Karoo and Succulent Karoo. Thirteen grid cells, mostly in the west of Western Cape, but with one further east in the Cape Fold Mountains, were simulated to have been consistently dominated by the Fynbos biome (Fig. 5(d)), whilst the biome was simulated consistently to occur in 67 grid cells (Fig. S3(d) in Appendix S3). The consistently dominated grid cells abutted 20 further grid cells, mostly to the east but also in the south of Western Cape, that were simulated to be dominated by Fynbos for at least 71 of the climate scenarios. Large areas of the north of the region were simulated to have been dominated by the biome for ten or fewer of the climate scenarios (438 grid cells, compared to 331 simulated to have been dominated by Fynbos for more than ten time slices, Table S6 in Appendix S3), these generally being grid cells that were simulated as dominated by the biome only under the climatic conditions of Heinrich Events.

Albany Thicket Biome

The Albany Thicket biome is today one of the least extensive of the regional biomes, accounting for only ca. 1.3% of the area being examined. Its extent was simulated generally to have been greater than today for most palaeoclimate time slices, with a mean extent almost 160% of that for 1961–90 (Figs. 3 & 4, Table S4 in Appendix S3). Its maximum extent, of more than three times that for the present, was simulated for the H3 climate, although unlike the preceding biomes it did not show a consistent direction of response of its extent to Heinrich Event climates. Instead, its extent increased for Heinrich Events H3 and H6, that coincide with summer insolation minima, but decreased for the other Heinrich Events, albeit generally only by small amounts. Its response to orbital forcing was clear, with peak extents coinciding with summer

insolation minima, and thus lagging peaks in extent of Fynbos, leading those for Nama Karoo and more or less corresponding to those for Succulent Karoo. At times of simulated greater extent during the last glacial stage, including those corresponding to Heinrich Event climates, it was simulated principally in an area of the east of the region, mostly in southern Mozambique, disjunct from its present area, whereas its peaks in extent during the LIG and more generally during MOI Stage 5 were principally extensions north-eastwards of its present area. No grid cells were simulated as consistently dominated by this biome, (Fig. 5(e)), indeed the most frequently dominated grid cell was only dominated for 47 time slices and only 16 grid cells were dominated by this biome for more than ten time slices (Table S6 in Appendix S3). The biome was simulated consistently to occur in only two grid cells (Fig. S3(e) in Appendix S3).

Grassland Biome

The Grassland biome was simulated generally to have had a greater extent than at present, peak extents coinciding with summer insolation peaks and maxima being simulated for Heinrich Events (Figs. 3 & 4). Greatest extents were simulated for Heinrich Event climates that coincide with summer insolation peaks, notably H1, H2 and H5, the overall maximum being simulated for the H2 climate, although the extent for H5 was almost as great, both being more than three times the present extent, with almost four times as many grid cells simulated to be dominated by the biome (Tables S4 and S5 in Appendix S3). At times of greater extent the biome generally extended principally north-eastwards, although under Heinrich Event climates it also showed a north-westward and general westward expansion (Fig. 3). At times of minimum extent, notably 124 ka when its simulated extent was at an overall minimum, it was constrained to the eastern part of its present extent. Forty grid cells in this eastern area, plus one outlying cell to the north-west, were simulated consistently to be dominated by this biome (Fig. 5(f), Table S6 in Appendix S3), with a further 56 surrounding grid cells simulated as dominated for more than 70 of the time slices considered. The biome was simulated to occur consistently in eighty grid cells (Fig. S3(f) in Appendix S3). More than half of the grid cells simulated as dominated on at least one occasion were so dominated on ten or fewer occasions (312 of 611 grid cells, Table S6 in Appendix S3).

Savanna Biome

The Savanna biome is today the dominant regional biome, extending over more than 58% of the area studied. For all but one of the time slices examined it was simulated to have been less extensive than today, the sole exception being 116 ka when it marginally exceeded its present extent; it was simulated to

reach a minimum extent of just less than half its present extent at 19 ka (Figs. 3 & 4, Table S4 in Appendix S3). Given its relatively modest simulated changes in relative extent, little detail can be seen on Fig. 4; its relative extent is therefore plotted on a more expanded scale in Fig. S4 (Appendix S3) where it is presented alongside the $\delta^{18}\text{O}$ record from the NGRIP Greenland ice core (Andersen *et al.*, 2004). As this latter figure shows, in contrast to the other biomes considered so far, that mostly show fluctuations in extent related to the precession cycles, the pattern of simulated change of extent of this biome closely parallels the Greenland ice core stable oxygen isotope record, with maximum extents during the Holocene and LIG, minimum extent more or less corresponding to the LGM, and a secondary minimum coinciding with Marine Oxygen Isotope Stage 4. Fig. S4 (Appendix S3) also reveals that this biome was simulated to increase in extent, albeit generally quite modestly, in response to Heinrich Event climates. Its reduced extent under glacial palaeoclimates corresponds to increased extents principally of the Grassland, Nama Karoo and/or Fynbos biomes at these times. Although the biome was simulated consistently to occur in 372 grid cells (Fig. S3(g) in Appendix S3), only 69 grid cells were simulated to be consistently dominated by this biome, most of these forming a block in northern Botswana, although with smaller blocks close to the border between Limpopo and Zimbabwe and in northern Zimbabwe and Mozambique (Fig. 5(g)). These areas are embedded within a near continuous area comprising 242 grid cells that were simulated to have been dominated for more than 70 of the time slices examined. Only a relatively small proportion (<25%) of cells dominated at some time by this biome was so dominated for ten or fewer time slices (Table S6 in Appendix S3).

Forest Biome

The Forest biome is the least extensive of the regional biomes today, occupying less than 0.4% of the region; it is also sparsely distributed with the result that it does not dominate even a single grid cell. Its mean simulated extent was almost 20% more than its present extent (Table S4 in Appendix S3), with a maximum extent more than twice that of today simulated for the 64 ka time slice. Peaks in its extent generally shortly precede summer insolation minima (Fig. 4) and thus more or less correspond to those in extent of the Albany Thicket biome. Heinrich Event climates in most cases led to simulated reductions in extent, although generally of small magnitude; H3, however, is an exception to this pattern with a simulated increase in extent by *ca.* 36% compared to the extent for the climate for 32 ka simulated by the 'normal' GCM experiment (Fig. 4, Table S4 in Appendix S3). Despite its increased mean extent this biome

did not dominate any grid cells under any of the climates considered, nor did it occur consistently in any grid cells, although it was simulated to occur for ≥ 70 time slices in 16 grid cells (Fig. S3(h) in Appendix S3).

Indian Ocean Coastal Belt (IOCB) Biome

The Indian Ocean Coastal Belt biome is another biome of relatively limited extent, today occupying only ca. 1.7% of the region, but with a concentrated distribution that leads to it dominating 31 grid cells. Its mean simulated extent was only ca. 75% of its present extent (Table S4 in Appendix S3), with minima and maxima in its extent more or less corresponding to minima and maxima in summer insolation (Fig. 4). Its extreme minimum extent, of only ca. 25% of its present extent, was simulated to coincide with the insolation minimum at 124 ka (Table S4 in Appendix S3), whilst it dominated a minimum number of grid cells at 60 ka (Table S5 in Appendix S3), again corresponding to an insolation minimum. Substantial and consistent increases in extent were simulated for the Heinrich event climates, with the overall maximum extent being simulated for H0, although with H3 and H4 giving almost as great an extent. Although simulated consistently to occur in 13 grid cells (Fig. S3(i) in Appendix S3), no grid cells were consistently dominated by this biome (Fig. 5(h)); the most frequently dominated grid cell was so dominated for 68 of the time slices, with a further four cells being dominated for >60 time slices. More than half of the grid cells dominated at some time were dominated for ten or fewer of the time slices examined (Table S6 in Appendix S3).

Simulated present avian species-richness patterns

The simulated patterns of present avian species-richness (Fig. S5 in Appendix S3) show two striking features. Firstly, although differing in details, overall richness (Fig. S5(a) in Appendix S3), as well as richness with respect to resident, mobile and intra-African migrant species (Fig. S5(b), (c) & (d) respectively in Appendix S3), show similar general patterns, with greatest species-richness in eastern areas, and especially in Mozambique, and lowest species-richness in the west. Secondly, endemic and near-endemic species show markedly different species-richness patterns from those of species as a whole (compare Figs. S6(a) & S5(a) in Appendix S3) , as well as between resident and mobile species. Resident endemic/near-endemic species (Fig. S5(e) in Appendix S3) have concentrations of grid cells with high species-richness in Western Cape, and to a lesser extent in western parts of Eastern Cape, and also in a second area spanning Limpopo, Gauteng and North West provinces. They also have scattered species-rich grid cells elsewhere, especially in northern Namibia and in Mozambique. In contrast, mobile endemic/near-endemic species (Fig. S5(f) in Appendix S3) have their greatest concentration of species-rich grid cells in an area spanning western parts of Eastern Cape, eastern parts of Western Cape and southern parts of Northern Cape, with smaller numbers of species-rich grid cells principally in Lesotho and Namibia.

Seasonality of precipitation

Seasonality of precipitation is a feature of the regional climate of southern Africa that is often viewed as of particular importance (Chase & Meadows, 2007), especially in relation to biome distribution. Changes in rainfall seasonality, and in the extent of winter, summer and year-round rainfall zones, over the past 140 kyr, were therefore explored and mapped. Seasonal rainfall zones were taken as those in which $\geq 60\%$ of annual precipitation fell during austral winter or summer, whilst regions where the winter/summer precipitation accounted for $>40\%$ but $<60\%$ of annual precipitation comprised a year-round rainfall zone.

Fig. S7 (Appendix S3) shows the extent of the seasonal rainfall zones for the present and 17 past time slices selected so as to illustrate both the most extreme contrasts, by including time slices from pairs most frequently giving maximum climatic differences, and the responses of climate to both orbital and sub-orbital forcings. Whilst emphasising that no one pattern persisted throughout the last glacial stage, several of the time slices shown have patterns consistent with that inferred by Chase and Meadows (2007) from various palaeoenvironmental records for the last glacial maximum. Fig. S8 (Appendix S3) illustrates the patterns of prevalence of winter, year-round and summer rainfall amongst the 79 time slices examined. Winter rainfall has high prevalence in the west (Fig. S8(a) in Appendix S3), where it also currently predominates (Fig. S7 in Appendix S3), especially in parts of the Fynbos and Succulent Karoo biomes, as well as in the western fringes of the Namibian desert region, with lower prevalence in a relatively small area to the east. Summer rainfall has been prevalent over much of the eastern and northern halves of the region (Fig. S8(c) in Appendix S3), although the area of highest prevalence is smaller than that of the present summer rainfall zone that extends over much of the Savanna and Grassland biomes (Fig. S7 in Appendix S3). A substantial area of lower prevalence lies to the south-west of the area of highest prevalence, with a smaller area of lower prevalence in the north-east. Only a relatively small number of grid cells, mostly in the present year-round rainfall zone that extends over much of the Nama Karoo and Albany Thicket biomes, as well as the eastern part of the Fynbos biome, has high prevalence of year-round rainfall (Fig. S8(b) in Appendix S3), with most of the area of lower prevalence lying to the east of the high prevalence area.

Fig. S9 in Appendix S3 shows the extent of the three rainfall zones for each of the 79 time slices expressed relative to their extent for the present climate. The most striking feature is the strength of the precession signal seen in the extents of the three zones, with the year-round zone in particular generally peaking in extent during austral summer insolation minima (see Fig. 4), whereas both the winter and summer rainfall

zones peak in extent principally during austral summer insolation maxima. This suggests that the main underlying factor here is a simulated weakening of the monsoon circulation when summer insolation is reduced, consistent with the lower prevalence areas of summer rainfall extending to the south-west of the core area of high prevalence of summer rainfall (Fig. S8(c) in Appendix S3), monsoon circulation bringing the summer rainfall to the east of the region. In contrast, the strength of both the summer monsoon and the westerly influence on winter rainfall are simulated to be increased when summer insolation is increased. The Heinrich Event stadials are also apparent in Fig. S9 (Appendix S3), but in this case it is the winter and year-round rainfall zones that increase in extent, whereas the summer rainfall zone decreases in extent. In this case it seems likely that the principal mechanism is increased westerly flow of warm moist air from the Atlantic during Heinrich Events, bringing greater precipitation to the two western zones, as illustrated and discussed by Huntley *et al.* (2014), the underlying mechanism being related to a simulated weakening and shift offshore of the upwelling zone that characterises the Benguela Current, and to a southward displacement of the Angola–Benguela Front, consistent with marine core evidence of such changes in circulation in the South Atlantic coincident with Heinrich Events (e.g. Kim *et al.*, 2003).

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